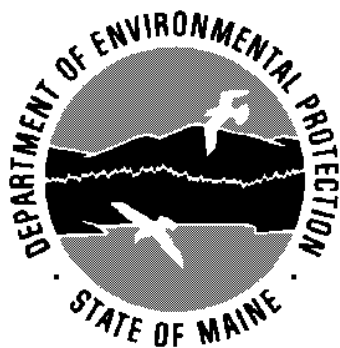# Aroostook River Modeling Report
# Draft
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# Executive Summary

1. A study of the Aroostook River from Ashland to the USA / Canada border (58 miles) began in the summer of 2001 involving the DEP and a number of stakeholders such as wastewater treatment personnel from Washburn, Presque Isle, McCain Foods, Fort Fairfield, and the Aroostook Band of MicMacs.

2. Two data sets were collected in August of 2001 to calibrate and verify a water quality model. The lack of runoff prior to the survey, presence of low flow conditions (second data set collected at 7Q10 flow), and utilization of good QA/QC measures resulted in excellent quality data to calibrate the water quality model.

3. Dissolved oxygen criteria were met at all Aroostook River and tributary sites with the exception of the three Presque Isle Stream sampling locations. Chlorophyll a results exceeded the algae bloom threshold (8 ug/l) at six Aroostook River locations from the Caribou dam to Fort Fairfield. For detailed descriptions of the data, one should consult the Aroostook River Data Report (MDEP, May 2002).

4. MDEP's version of the EPA supported model, QUAL2EU, (QUAL2MDEP) was used to model the Aroostook River and two tributaries (Presque Isle Stream and Little Madawaska River). Some important changes to QUAL2EU include the addition of a periphyton module and benthic BOD component, an enhanced dissolved oxygen saturation calculation that adds salinity as a dependent variable, and alteration to phosphorus output units to the nearest 0.1 ppb.

5. The model was calibrated and verified with comparisons of the model output of BOD, phosphorus, nitrogen, chlorophyll-a and dissolved oxygen to the data observed in the summer of 2001. Good comparisons resulted.

6. The model prediction runs at worse case conditions of 10-year low flow, high water temperatures, and point sources inputted at licensed loads predicts that both minimum dissolved oxygen criteria and monthly average dissolved oxygen criteria (6.5 ppm) should be met everywhere on the Aroostook River. Algae blooms are projected to occur in about 27 river miles from Presque Isle to Fort Fairfield.

7. Point sources inputted at licensed conditions account for about 87% and 96% of the total BOD and phosphorus loads, respectively, that enter the Aroostook River at 7Q10 flow conditions.

8. Collective point source phosphorus reductions of greater than 50% from current amounts are needed to eliminate algae blooms. The most important sources to reduce are McCain Foods and Presque Isle. The model runs indicate that blooms can be eliminated when these two point sources inputted at a TP concentration of 0.5 ppm.

9. Data taken in the summer of 2002 indicates that the algae also cause pH to exceed the maximum allowable level of 8.5.

10. Non-point source best management practices should be implemented on priority tributary watersheds.

11. An additional data set should be taken at reduced point source phosphorus inputs. McCain Foods and Presque Isle should target TP levels of 1 ppm. Fort Fairfield should implement phosphorus pollution prevention during this data collection effort.

# Table of Contents

# Figures

## **Tables**

## Introduction

The Aroostook River Basin is the largest sub basin of the St John River lying almost entirely within the state of Maine. It has a drainage area of 2353 square miles at the international border of U.S. and Canada. The river segment of interest on the Aroostook begins in Ashland (River Mile 58) and flows to Washburn (RM 37), Presque Isle (RM 28), Caribou (RM 14), Fort Fairfield (RM 3) and eventually the international border (RM 0). In Canada, after an additional 4.6 miles, the Aroostook joins with the St John River.

A water quality model has been developed to update a prior effort. A model calibration data set was collected in 1987. A water quality model was setup on the USEPA supported model, QUAL2EU, but an additional verification data set to complete the model was never collected. The two low flow data sets collected in the summer of 2001 were used to calibrate and verify the water quality model. The model is then typically used to predict worst case (low flow, high water temperature) water chemistry of such parameters as dissolved oxygen, algae, or nutrients. Regulatory measures on both point and non-point source pollutant inputs may be necessary if the model predictions for dissolved oxygen are lower than statutory requirements.

The data collection effort involved stakeholder participation from the towns of Washburn, Presque Isle, Fort Fairfield; McCain Foods; the Aroostook Band of MicMacs; and personnel from MDEP, Augusta; and the Northern Maine Regional Office of DEP in Presque Isle.

In the river segment of interest, seven point source discharges are licensed to discharge organic waste loads to the Aroostook River. Point source discharges and their permitted licensed flows are as follows: Ashland (0.3 mgd), Washburn (0.28 mgd), Presque Isle (2.3 mgd), McCain Foods (2.5 mgd), Caribou (1.41 mgd), Loring (2.5 mgd), and Fort Fairfield (0.6 mgd). Two dams significantly impound water in this segment. The Caribou dam is located approximately 15 river miles upstream of the international border and impounds water 4.5 river miles above the dam. The Tinker dam is located in Canada, but still impounds water 5 river miles upstream of the international border. Non-point source (NPS) inputs related to agricultural and forested land uses are also possible relevant pollution sources to the Aroostook watershed.

| Table 1  Point Source Discharges to Aroostook River | | | | | |
|---|---|---|---|---|---|
| | Flow | BOD5 Mo Ave | BOD5 Weekly Ave | BOD5 Daily Max. | TP Weekly Ave |
| | mgd | PPD | PPD | PPD | PPD |
| Ashland | 0.3 | 75 | 113 | 125 | |
| Wasburn | 0.28 | 70 | 105 | 117 | |
| Presque Isle | 2.3 | 168 | 168 | 168 | 3.8 |
| McCain Foods | 2.5 | 794 | N/A | 2077 | 91 |
| Caribou | 1.41 | 880 | N/A | 1595 | |
| Loring | 2.5 | 626 | 938 | 1043 | |
| Fort Fairfield | 0.6 | 556 | N/A | 1078 | |

## Summary 2001 Data

The data collection effort is described in detail in the Aroostook River Data Report (May 2002).  Some highlights are repeated here for convenience.  The overall quality of both the data sets collected in 2001 is considered excellent due to good QC measures utilized throughout the sampling effort that involved such practices as cross checking of dissolved oxygen meters and duplicate sampling.  The three-day intensive surveys, that were undertaken on August 14 ,15, and 16 and August 28,29,and 30 were specifically for calibration and verification of the water quality model.  It is desirable to collect the model calibration data sets under conditions of low flow and high water temperature.  This represents conditions of worse case when river dissolved oxygen levels are most likely to be the lowest.  At low river flow, the dilution of waste loads is reduced resulting in river pollutant concentrations of higher strength.  At high water temperatures, dissolved oxygen saturation decreases and biological activity increases resulting in a greater amount of oxygen demand in the water column as BOD (biochemical oxygen demand) and greater amount of oxygen demand from bottom sediments (SOD).  Thus water column dissolved oxygen depletion is maximized under these conditions.

A goal of sampling at less than 390 cfs as measured at the USGS gage in Washburn (90% flow duration) was the specified target flow in the Work Plan for the three-day intensive survey.  This goal was met in both intensive surveys.  The three-day average flow was 145 and 127 cfs for the first and second data set, respectively.  When considering 7-day low flows, the first data set represents about a 6-year event and the second data set a 10-year event.  The 7-day 10-year (7Q10) flow is used for calculating the river's assimilative capacity.  Hence the river was sampled under ideal flow conditions.

Another preferable sampling condition is having no runoff during and prior to the survey.  Runoff is undesirable due to the difficulty of quantifying it as input to the model.  The first data set had minimal rainfall prior to and during the survey.  The second data set had some precipitation events a week prior to sampling which resulted in about a 10% rise in river flow at Washburn over two days.  In addition, there were precipitation events during the second survey which resulted in the river flow at Washburn rising 24% over the three day period.  This is still within the limits specified in the work plan in which flow

increases from runoff should not 50% for the data to be considered acceptable for model calibration.

The dissolved oxygen data are characterized by large diurnal fluctuations due to the significant growths of both bottom-attached (benthic) and floating algae (phytoplankton). There is similarly a trend of greater fluctuation in the shallower flowing sections and less fluctuation in impoundments (figure 6). There is also a trend of less fluctuation above the significant point source discharges. In the segments above major point source discharges (first five upstream locations and background tributary) average diurnal DO fluctuations are generally around 1 to 2 ppm. Below major point source discharges, average diurnal DO fluctuations range from 5 to 9 ppm in the shallower flowing segments and 1 to 4 ppm in impoundments.

The 2001 data indicated that minimum statutory dissolved oxygen criteria were met and often greatly exceeded at all river and tributary locations, except in Presque Isle Stream. Of significance, however was the fact that point source discharges were collectively at only 4% of their licensed permitted BOD5 (five-day biochemical oxygen demand[1]) limits. Hence the potential for lower dissolved oxygen levels than measured is possible, and worse case levels must be determined by the model.

A chlorophyll-a[2] level of 8 ug/l is used as a threshold level indicating the occurrence of an algae bloom. When chlorophyll a levels approach this threshold, the water may begin to appear green tainted from plankton that are floating in the water. The plankton may also be visible within the water column. Both data sets experienced chlorophyll a levels exceeding the threshold from above the Caribou dam to the international border.

Although not quantitatively sampled, large levels of benthic algae were observed in the Aroostook River during both surveys. The benthic algae were evident from the confluence of Presque Isle Stream to the head of the Caribou dam impoundment, but most abundant from below the Caribou dam to the head of the Tinker Dam impoundment in Fort Fairfield. Benthic algae were also observed in Presque Isle Stream.

## **Water Quality Model**

The EPA supported model, QUAL2EU was used in the analysis of the Aroostook. Steady state flows and load inputs are required and major transport mechanisms of advection and dispersion must be one-dimensional. The lack of significant runoff that was previously discussed satisfies the steady state condition. The uniformity of the dissolved oxygen and temperature readings in the vertical profiles indicates that the

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[1] Biochemical oxygen demand (BOD) is a laboratory test estimating the amount of oxygen demanding substances in water samples. The oxygen depletion of a water sample is measured over a time increment. The five-day test or BOD5 is typically used to measure BOD in effluent samples from wastewater treatment plants. Hence, this test measures the potential of discharges to deplete oxygen within a river.
[2] The chlorophyll-a test is used as an indicator to quantify the amount of phytoplankton or floating algae within a water sample.

Aroostook is a well-mixed system and hence one-dimensional flow occurs. The Aroostook River should be well suited to this model.

Many changes were recently incorporated into MDEP's version of QUAL2EU or more appropriately named QUAL2MDEP. The changes are as follows:

1. Addition of a periphyton module with links to the nutrient and dissolved oxygen modules. A major shortcoming of QUAL2EU is bottom attached algae can not be directly modeled. The majority of impacts now experienced in rivers involve low early morning dissolved oxygen from bottom attached algae. The QUAL2MDEP model can now be used to model bottom attached algae and the resulting diurnal dissolved oxygen swings.

2. Addition of a benthal BOD component. QUAL2EU models the direct oxygen demand from bottom sediments, but the sediment may also add BOD to the water column. This is particularly significant in long river systems like the Aroostook with long travel times to accurately model non-point source impacts.

3. Enhancement of the dissolved oxygen saturation calculation. QUAL2EU calculates dissolved oxygen saturation as a function of temperature. This results in unnecessary error in marine situations, since salinity also affects dissolved oxygen saturation. Salinity is now included into the dissolved oxygen saturation calculation.

4. Alteration to phosphorus output units. QUAL2EU's output for organic phosphorus and dissolved phosphorus is rounded off to the nearest 10 ppb. This has been changed in QUAL2MDEP so the output for phosphorus components are now rounded off to the nearest 0.1 ppb.

5. Revisions to the simulation output formats. The diurnal output was enhanced so that all dynamic output can now be observed. An EXCEL VBA post processor was created. The output for a dynamic model run is quite large and not easily managed. The postprocessor allows the selection of specific output specified by the user, which can be transferred to an EXCEL spreadsheet for observation and easy plotting.

The first step in the model setup is to divide the river into segments of similar physical and chemical properties called reaches. The model has 26 reaches, and 12 point source inputs (figure 1). The water quality classifications are illustrated in Figure 2. Presque Isle Stream and the Little Madawaska River are modeled as tributaries with junctions containing three and five reaches, respectively. The other major non-point source tributary inputs are modeled as point sources. There are 7 point source inputs and 5 major tributary inputs. The minor tributaries are grouped into incremental inputs or inputs with flow distributed throughout the reach. Phytoplankton as chlorophyll-a, nutrients as nitrogen and phosphorus, carbonaceous BOD, periphyton, and dissolved oxygen were simulated as the chemical parameters of interest.

## Model Transport

In the hydraulic component of the model, river velocity and depth relationships are developed as a function of flow. Transect and time of travel data are used as a basis for deriving the relationships. QUAL2EU offers two options for the transport of pollutant parameters; a power equation and the Manning equation for open channel flow. The

power equation option was chosen for the Aroostook River model.  This computes
velocity and depth as a function of flow with the following equation:

$$V = A_1Q^B_1 \text{ and } D = A_2Q^B_2$$

where V = velocity;  D = depth;  Q = flow, and $A_x$, $B_x$ are coefficients that are
empirically derived from transect and time of travel data

Two sources of information were available for developing hydraulic relationships (Table
2).  A dye study sampled at three river flows from Washburn to Fort Fairfield was
undertaken by the NMRO of DEP in 1971.  Little information is available on this study
other than travel times at the specific flows (Figure 3).  Transect data was undertaken at a
number of dates and locations.  The transect data for the Tinker Dam impoundment were
collected in the early 1990's.  Transect measurements were taken in 2001 at 24 locations
and were supplemented with additional data taken in 2002 at 19 locations.

The indicated river velocities are somewhat different when comparing the transect and
dye study information.  The velocity from both sources of information were averaged as
input for the model (Figure 4).  In the river segment from Ashland to Washburn and Fort
Fairfield to the international border no dye study information was available.  In these
areas, the transect data were used as the source for determining river velocities.

Flow data is available at two USGS gages on the Aroostook River; one at Masardis and
the second at Washburn.  In addition, flow was gaged on the following tributaries during
the survey; Caribou Stream, the Little Madawaska River and Presque Isle Stream.  A
flow balance was calculated for the watershed (table 3) using this available flow
information and a proration of watershed drainage area for tributary inputs to the
Aroostook.  The larger tributaries were input to the model as point sources and the
smaller tributaries were grouped as incremental flow inputs or distributed loads.

## Chemical Calibration of the Water Quality Model

The chemical calibration of the model involves inputting measured tributary and
treatment plant effluent as point source loads, measured upstream boundary conditions
and measured water temperature as initial conditions.  The model output of various
parameters, such as BOD, chlorophyll a, and dissolved oxygen are compared to measured
values and adjustments are made to the model parameter rate coefficients until a good
match of model and observed values occur.  The model parameter rates that are adjusted
include many inputs (see Tables 4, 5).  Default values are used as initial estimates and
adjusted within the ranges recommended in the literature until satisfactory results are
achieved.  The model is verified after satisfactory results are obtained from a comparison
of modeled Vs observed values of a second independent data set.  After this process, the
model can then be reliably used for model predictions of water quality.

The data collected on August 28, 29, and 30 were used to calibrate the Aroostook River
water quality model.  These data were collected under lower flow conditions than the
data collected earlier that month and should have a higher sensitivity to parameter rate
adjustments.  The data collected on August 14, 15, and 16 are used to verify the model.

The model calibration / verification are plotted for each chemical parameter (figures 5 to 11) in a river mile Vs chemical parameter format. The model output is displayed as a line and the data as an average (unshaded triangle) and range (high and low error bars).

The calibration and verification of the model was problematic, due to the unstable and highly dynamic nature of a river that is dominated by algal interactions. As mentioned earlier, the difference between the early morning and late afternoon dissolved oxygen readings (diurnal DO range) was often 6 ppm and as much as 10 ppm. This system is very complex and is marginally within the limits of application of water quality models for predictions.

In addition, there is a large loss of nitrogen and phosphorus (orthophosphorus in particular and organic phosphorus, nitrogen ,and nitrate nitrogen to a lesser extent) below some of the point source discharges that is assimilated quickly in a relatively short distance (1 to 2 miles). For example, 80% to 90% of the orthophosphosphorus is assimilated below the Presque Isle and Caribou discharges in one to two miles of river length. The model had difficulty simulating this phenomena. It is deduced that large quantities of orthophosphorus are being uptaken by bottom attached plants. To compensate for this phenomena, a orthophosphorus uptake rate was included in the modeling effort. This is not directly included in the model, but can be simulated by assignment of negative flux rate into sediments (which is actually uptake by the benthic algae).

The traditional approach used by modelers when assigning parameter rates is to use the same rate for model calibration and verification. In reality, the rates are somewhat variable. The rates assigned for the algae component of the model that is the most complex part of the model and the environment are the rates that are most likely to vary. The approach used for the Aroostook model is to use a constant rate for model calibration and verification whenever possible. In 33 of the 37 rates assigned, constant rates were used for both data sets (Table 4). Variable rates were used for the benthic CBOD rate, organic phosphorus settling rates, orthophosphorus uptake rate, and the algal loss coefficient (Table 5).

A benthic CBOD source rate was assigned to all model reaches. This value varied from 10 to 80 mg / ft$^2$-day. Some user judgement is necessary when assigning this rate. The rates assigned to the model resulted in an improved BOD calibration when using the measured laboratory rates in the BOD calibration. A low rate of 10 mg / ft$^2$-day was assigned to reaches with low impact from point source discharges, which includes the river reaches from Ashland to the confluence of Presque Isle Stream and the Little Madawaska River. A rate of 40 mg / ft$^2$-day was used in areas impacted by point sources, except 80 mg / ft$^2$-day was used in the Caribou dam impoundment on the first data set. The higher benthic BOD assigned in impoundments may actually be due to algae that settles in the impoundments. The algae measured in the first data set above the Caribou dam was about 50% higher than the second data set.

In a large river with impoundments where currents are not significant, the UBOD decay rates derived in the laboratory test often give satisfactory results for an estimation of the actual ambient rates. The Aroostook River falls into this category river type. The laboratory rates are derived from a least square regression line fit of many UBOD values measured over the 60 day time period. The following equation is used in this analysis.

**$BOD_t = UBOD (1-e^{-kt})$**    Where $BOD_t$ = BOD in ppm at any given time
UBOD = The final ultimate BOD in ppm
K = The BOD decay rate (/day)
T = Time in days.

A CBOD decay rate of 0.05 per day was used for both the calibration and verification data sets. This resulted in a satisfactory match of modeled to measured ultimate CBOD (Figures 5a, 5b).

Nitrogenous BOD decay is not an issue on the Aroostook River. At almost all river locations, the measured value of ammonia nitrogen was under the detection limit of 0.04 ppm.

The chlorophyll-a was calibrated and verified as follows. There are many different parameter rates that can be adjusted when calibrating chlorophyll a. Most of these were set to default values. For the algae growth rate, MDEP's experience in modeling phytoplankton has almost always resulted in an algae growth rate of 1.8 to 2.0 per day. For the Aroostook, a value of 1.8 per day was used. This initially resulted in modeled chlorophyll-a being lower than measured. The algal loss coefficient was next adjusted lower in some reaches until a satisfactory match of modeled to measured chlorophyll a occurred (Figures 6a, 6b).

Although referred to in the Qual2e users manual as algal settling, the settling term actually represents algal losses due to settling, death, and zooplankton grazing (the latter two of these are not separately included in the input coefficients for Qual2e). Hence in the Aroostook Modeling Report, it is referred to as an algal loss coefficient. In most modeled reaches, a algal loss coefficient of 0.2 ft/per day and 0.1 ft/per day, respectively for the first and second data sets gave the best results.

In the reach below the Caribou dam, the data indicate that large losses of algae are occurring. This is most likely due to the change of algae type from a phytoplankton dominated sytem to that of benthic dominated algae as the river changes from impounded to free flowing. A rate of 1.0 ft/day gave the best result in both data sets for this reach.

In the Tinker dam impoundment, there appeared to be a larger loss of algae in the first data set when compared to the second data set. The exact reason for this is unknown. An algal loss coefficient of 1.5 ft/day was assigned to reaches here in the first data set.

As mentioned earlier, there appears to be a large loss of dissolved phosphorus below point source discharges. The exact reasons for this are uncertain, but two possible reasons are discussed. One theory could be that a microhabitat of lush bottom plant growth may be occurring directly below outfall pipes as the river's response for alleviating abnormally high phosphorus levels here. This could result in a rapid uptake of nutrients. To a lesser extent, the settling of orthophosphorus could be occurring. Although dissolved solids do not ordinarily settle, other studies have shown that orthophosphorus can attach onto particulate solids through adsorption. The phosphorus uptake rate assigned as a negative flux to the sediments was used to simulate both phenomena. This was used as the main mechanism to calibrate orthophosphorus. To a lesser extent, this loss phenomena also occurs for organic phosphorus and organic nitrogen. Adjustments to the settling rate were used to calibrate these parameters.

The phosphorus loss inputs were generally adjusted to very high rates below point source discharges and lower rates in less impacted areas. When these and some other adjustments were made to the model, a good calibration of chlorophyll-a and nutrients results (figures 7a, 7b, 8a, 8b, 9a, 9b).

The dissolved oxygen calibration involves both a daily average calibration and a daily minimum calibration. The former involves running the model in the steady state mode and comparing the model output to the daily average dissolved oxygen observed in both data sets. The latter involves running the model in the dynamic mode and comparing the model output to the AM and PM dissolved oxygen observed in both data sets.

The calibration of dissolved oxygen involves the initial steps of calibrating BOD, chlorophyll a, and nutrient and subsequent steps of estimating the reaeration rate ($K_a$) and sediment oxygen demand rate (SOD) for each modeled reach of river[3]. Then the periphyton component of the model must be adjusted so that both diurnal and daily average dissolved oxygen outputted by the model match the data. $K_a$ and SOD are typically very variable over the length of a river and the rates assigned can be quite different reach by reach.

There are a number of formulas to estimate reaeration based upon research by experts. Up to eight different formulations can be specified by the user in QUAL2. The O-Connor Dobbins reaeration formula which calculates reaeration as a function of velocity and depth was used in most reaches.

$$\mathbf{k_a = 12.85\ V^{.5}/D^{1.5}}$$ where v = velocity in fps, and D = depth in ft

In the deeper and lower velocity reaches, $k_a$ was calculated by an impoundment reaeration formula which is considered a lower bound for $k_a$ whenever the O Connor-Dobbins formula results in a lower estimate.

$$\mathbf{k_a = 3/D}$$

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[3] The reaeration rate, $K_a$, is the rate at which oxygen from the atmosphere enters the water column at the surface. $K_a$ is typically high in stretches of rapids or shallow water, and low in impounded or sluggish water. Sediment oxygen demand is the oxygen demand exerted by bottom sediments to the water column.

This option is not directly available in QUAL2, but can be calculated outside the model and input as a user specified rate. The reaeration rates calculated by the model were quite variable ranging from a low of 0.25 per day directly above the Caribou dam to a high of 20.38 per day on the Little Madawaska River (Table 5).

SOD analyses at two river impoundment locations were undertaken in the autumn of 2001 by USEPA. The measured values of 50 and 85 mg / $ft^2$-day were used for the Caribou dam and Tinker dam impoundments, respectively. A lower value of 10 mg / $ft^2$-day was used for the free flowing river sections from the Caribou dam to the head of the Tinker dam impoundment and the Little Madawaska River segments.

A higher SOD rate of 150 mg / $ft^2$-day was used in the upper reaches of the Aroostook (Ashland to Prsque Isle). The model predicts higher dissolved oxygen than measured here, when an input SOD rate equivalent to the Caribou dam impoundment was used. The reason for this appears to be the unusually high algae and periphyton oxygen production rates used for the model. This rate cannot be assigned as a reach variable rate and may be inappropriate for this section of the river where algae levels are low compared to the river below the confluence of Presque Isle Stream. Adjustments to other parameters were considered without success (Table 6).

| Table 6 Dissolved Oxygen Calibration Sensitivity Upper Aroostook | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Dissolved Oxygen (ppm)** | | | | | | | |
| Sample Location | Data Ave DO (ppm) | Aug 28-30 Calibration | Run 1 | Run 2 | Run 3 | Run 4 | Run 5 |
| Rte 11 Ash. | 8.19 | 8.19 | 8.19 | 8.19 | 8.19 | 8.19 | 8.19 |
| Ashland Below | 8.39 | 8.32 | 8.67 | 8.67 | 8.72 | 8.3 | 8.47 |
| Washburn | 8.21 | 8.54 | 8.94 | 8.93 | 8.81 | 8.68 | 8.72 |
| Crouseville | 8.18 | 8.65 | 9.15 | 9.14 | 9.15 | 9.08 | 8.6 |
| Above Rte 1 Presque Isle | 8.62 | 8.56 | 9.15 | 9.13 | 9.01 | 9.66 | 8.4 |
| **Model Inputs** | | | | | | | |
| SOD (mg/$ft^2$-day) | | 150 | 50 | 50 | 50 | 50 | 50 |
| Velocity (ft/sec) | | .4 - .72 | Same | Same | x .5 | Same | Same |
| Reaeration (/day) | | 3.75 - 9.07 | Same | Same | Lower* | 1 | 1 |
| Benthic CBOD (mg/ft2-day) | | 10 | Same | 40 | Same | Same | Same |
| O2 Production Algae/Peri | | 20 / 6 | Same | Same | Same | Same | 1.6 / 1.6 |

*Lower reaeration due to less velocity.
The SOD rate of 150 mg/$ft^2$-day is being used to assure that the boundary DO above Presque Isle predicted by the model is accurate. The model may eventually be discontinued above Presque Isle, due to the low probability of water quality issues there.

The diurnal range of dissolved oxygen (minimum AM and maximum PM DO) were used to calibrate the periphyton component of the model. No direct measurements of periphyton were made. Periphyton, filamentous algae such as Cladaphora, and vascular plants (macrophytes) could all contribute to the diurnal dissolved oxygen swing. In a

river that is so abundant with algae, this would be difficult to measure accurately. The dissolved oxygen range measures the response of bottom attached plants. This is analogous to the BOD test in which organic matter is not measured directly, but the response of organic matter or dissolved oxygen depletion is used as a measure of oxygen demanding substances.

The parameter rates used for each model reach are summarized in tables 4 and 5. To calibrate dissolved oxygen, values of oxygen production by algae and periphyton (20 and 6, respectively) are much higher than literature values. There are no adjustments that can be made to the model within literature values that will result in a good calibration. Much of the dissolved oxygen data is supersaturated (> 100% saturation) and it is unclear if the model can perform as well under these conditions. The calibration of dissolved oxygen with these parameter rates results in a good fit of the model output to the daily average (Figures 10a and 10b) and daily minimum of the measured data (Figures 11a and 11b).

## Sensitivity Analysis

In a sensitivity analysis, some of the parameter rates can be tested to determine which are more important in the development of the model. The model calibration run (Aug 28-30) was used as a basis for the sensitivity analysis runs. Fifteen different parameter inputs are tested (Table 8a,b) for responses to dissolved oxygen, carbonaceous BOD, chlorophyll a, periphyton, and orthophosphorus. Each parameter was varied by $\pm$ 50% and the model output for the five water quality constituents was then compared at three strategic locations. The three locations chosen are above the Caribou dam, Goodwin, and at the international border in the Tinker dam impoundment. The two impoundment sites had the highest phytoplankton levels, and the Goodwin site, the highest diurnal DO swings and hence the highest levels of bottom attached plants.

The results of the sensitivity analysis are first tabulated in units as $\pm$ (Table 8a) and then as average percentages (Table 8b). It should be apparent that the algae rates were most sensitive in the impoundment locations (Caribou dam, international border) and the periphyton rates in the flowing section (Goodwin).

From this analysis, it can be observed that the most important parameters in calibrating dissolved oxygen are the reaeration rate, algae or periphyton growth rates, orthophosphorus uptake rate, and the algae or periphyton oxygen production rates. For the BOD calibration both the BOD decay rate and the CBOD benthic source rate are important. For the chlorophyll a calibration, the algae growth rate, the orthophosphorus uptake rate, and the algae loss coefficients are the most important parameters. The periphyton growth rate and orthophosphorus uptake rate are the most important parameters for the model's prediction of periphyton. The orthophosphorus uptake rate is the main parameter responsible for the calibration of PO4-P and to a lesser extent, the algae growth rate is important.

It should be understood that one of the primary reasons for the orthophorus uptake rate sensitivity in these runs is that when this rate is increased by 50%, the river's orthophorus goes to zero, which result in the total depletion of any algae and the related oxygen production. Hence a threshold of phosphorus limitation is crossed. In the actual calibration / verification of the model, the necessary precautions would be taken by the modeler to assure that this threshold isn't crossed. The sensitivity analysis was undertaken and tabulated in a uniform way rather than arbitrarily conducting the analysis to avoid crossing this threshold.

## Model Predictions Runs of Current Conditions at 10-Year Low Flow

After a water quality model is calibrated to observed data, a prediction run is made at worst case conditions to assure water quality standards will be achieved at all locations. Worse case conditions are defined by low river flows, when dilution of wastewater is at a minimum; by high water temperatures, when the saturation of dissolved oxygen is lower and BOD decay and oxygen demand from the sediment are higher; and by point sources discharging at licensed limits. Non- point source loads are accounted for as tributary loads with pollution concentrations as measured in the August 2001 surveys, distributed load inputs in the model incremental flow, and as sediment oxygen demand (which results partially as sediment that has settled during runoff events prior to low flow).

The 7-day 10-year low flow (7Q10)[4] is used to assess compliance with dissolved oxygen criteria. Prior estimates of 7Q10 were based upon USGS gages utilizing the period of record up to 1991. This analysis was updated to also include the years from 1992 to 2002. The updates resulted in new 7Q10's of 116 cfs at the Washburn USGS gage and 67 cfs at Masardis USGS gage (Figure 12). The updated information for flow results in new 1Q10 flows of 106 cfs at Washburn and 60 cfs at Masardis. The previously derived flow balance (Table 3) was used to determine various 7Q10 flows and 1Q10 flows at different locations. Dilutions for the toxics program regulation for point source discharges (Chap. 530.5) will be changed based upon this updated information (Table 8).

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[4] The 7-day 10-year low flow (7Q10) is the lowest 7-day average flow expected to occur at a frequency of once in ten years. The 1-day ten year low flow (1Q10) is the lowest single day flow expected to occur at a frequency of once in ten years.

## Table 8  Summary of Point Source Dilutions for Toxics Program

| | River | New Flow Statistics 7Q10 | New Flow Statistics 1Q10 | | Old Flow Statistics 7Q10 | Old Flow Statistics 1Q10 |
|---|---|---|---|---|---|---|
| Masardis Gage | Aroostook | 67 | 60 | | 85 | 79 |
| Washburn Gage | Aroostook | 116 | 106 | | 146 | 122 |
| Presque Isle Stream above WWTP | | | | | 8.3 | 7.1 |
| Little Madawaska R above WWTP | | | | | 10.7 | 9.1 |

| | River | New Flow Statistics 7Q10 | New Flow Statistics 1Q10 | WWTP Flow MGD | Old Dilution Chronic | Old Dilution Acute | New Dilution Chronic | New Dilution Acute |
|---|---|---|---|---|---|---|---|---|
| Ashland | Aroostook | 98 | 90 | 0.30 | 263 | 220 | 212 | 194 |
| Washburn | Aroostook | 116 | 106 | 0.28 | 335 | 141 | 268 | 245 |
| Presque Isle | Aroostook | 126 | 115 | 2.30 | | | 36 | 33 |
| Presque Isle | Presque Isle Str | 3.0 | 2.7 | 2.30 | 2.3 | 2.0 | 1.8 | 1.8 |
| McCain Foods | Aroostook | 126 | 115 | 2.50 | | | 34 | 31 |
| Caribou | Aroostook | 134 | 122 | 1.41 | 80 | 68 | 62 | 57 |
| Loring | Little Madawaska | 28 | 26 | 2.50 | 3.8 | 3.3 | 8.2 | 7.6 |
| Fort Fairfield | Aroostook | 162 | 148 | 0.60 | 206 | 173 | 175 | 160 |

Note: Presque Isle Stream and Little Madawaska new statistics based upon flow measurements in the summer of 2001during a 7q10 event.

Two tests are run with the water quality model to check dissolved oxygen compliance with statutory criteria; one to test compliance of minimum dissolved oxygen criteria and a second to test compliance with the monthly average criteria of 6.5 ppm.  In the first test assessing compliance with minimum dissolved oxygen criteria, river flows are inputted as 7Q10; river temperatures are inputted as a weekly average; and point sources are inputted at their weekly average licensed loads.  In the second test assessing compliance with monthly average dissolved oxygen criteria, river flows are inputted as 30Q10; river temperatures are inputted as a monthly average; and point sources are inputted at their monthly average licensed loads.

The river temperature used for 7Q10 was based upon the first August data set in 2001 which contain higher temperatures than the second data set.  The temperatures assigned to the model begin at 22 $^{o}$C for the upper Aroostook in the free flowing regions and eventually increase to 24 $^{o}$C in impounded river sections.

In both these runs, pollutants that are not included in the license such as nitrogen or phosphorus are ordinarily inputted as measured in the calibration data.  The ultimate point source BOD must be derived from the product of a BODu/BOD5 ratio (which is derived from data) and the licensed BOD5 concentration.  Point source inputs to the model is summarized in table 9.

| **7Q10** | Licensed Parameters | | | | | Model Input | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Flow | Monthly Ave. | BOD5 Weekly Ave | BOD Daily Max. | CBODu/ BOD5 | CBODu Mo Ave Week Ave | ON | NH3-N | NO3-N | Chl-a | OP | PO4-P |
| | mgd | PPD | PPD | PPD | | PPM | PPM | PPM | PPM | PPB | PPM | PPM |
| Ashland | 0.3 | 75 | 113 | 125 | 2.91 | 87 131 | 1.99 | 0.24 | 0.03 | 80 | 0.88 | 0.46 |
| Wasburn | 0.28 | 70 | 105 | 117 | 10.34 | 310 465 | 9.42 | 1.8 | 1.33 | 608 | 2.33 | 3.03 |
| Presque Isle* | 2.3 | 575 | 863 | 959 | 3.54 | 106 159 | 1.7 | 0.1 | 6.02 | 4.8 | 0.2 | 1.7 |
| McCain Foods | 2.5 | 794.0 | 1869 | 2077 | 3.52 | 134 316 | 46.9 | 0.08 | 0.26 | 6.4 | 0.62 | 3.75 |
| Caribou | 1.41 | 880 | 1436 | 1595 | 2.26 | 169 276 | 10.1 | 0.39 | 13.6 | 71 | 0.3 | 1.4 |
| Loring | 2.5 | 626 | 938 | 1043 | 3.64 | 109 164 | 1.48 | 0.04 | 3.1 | 0.6 | 0.57 | 0.56 |
| Fort Fairfield | 0.6 | 556 | 970 | 1078 | 1.8 | 200 349 | 9.9 | 2.47 | 28.2 | 1.5 | 0.73 | 2.44 |

**Table 9  Point Source Inputs at 10-Year Low Flow**

Note:  McCain Foods, Caribou, and Fort Fairfield are not licensed as a weekly average.   This was assigned in the model run by the product of 0.9 and the daily maximum licensed BOD5.

* Assumed inputs for Preque Isle with outfall re-located to the Aroostook River.  BOD5 is BPT and no immediate phosphorus limit.

The classification of the Aroostook River is class B from Ashland to the confluence of Presque Isle Stream.  Below the confluence of Presque Isle Stream it is class C to the USA / Canada border with the exception of a 3-mile segment above the Caribou water supply intake (which is near the Caribou dam).  The water quality classifications are illustrated in figure 2.

The dissolved oxygen criteria is as follows:

Class B        Daily minimum $\geq$ 7.0 ppm and 75% of saturation
Class C        Daily minimum $\geq$ 5.0 ppm and 60% of sat.;  monthly average $\geq$ 6.5 ppm

Currently the general provisions section of the water quality classification law states that discharges cannot cause the pH of waters to fall outside the range of 6.0 to 8.5.

In river systems with significant levels of algae, a daily minimum dissolved oxygen level typically occurs in the early morning hours. During the evening hours, the lack of light results in extended respiration of algae and the continuous consumption of oxygen in the river.  During the daytime, oxygen that is produced through photosynthesis greatly exceeds the oxygen consumed through respiration resulting in a maximum river dissolved oxygen concentration in mid to late afternoon.  The difference between the minimum and maximum daily dissolved oxygen in the river is referred to as the diurnal swing of dissolved oxygen.  There is similarly a diurnal trend in pH in rivers that are eutrophic

which results in a minimum pH at dawn and a maximum pH in the afternoon hours. Afternoon pH readings can often exceed 8.5 in a highly eutrophic river system. The time of day in which water quality criteria are most likely to be not met in eutrophic river systems is dawn for dissolved oxygen and the afternoon hours for pH.

The model must be run in the dynamic mode for predictions of the daily minimum dissolved oxygen.  The model prediction run of point sources discharging licensed amounts indicates that minimum dissolved oxygen criteria should be met in all portions of the Aroostook River.  Large diurnal dissolved oxygen swings are predicted that are similar to the measured swings in the calibration data sets (figure 13).

In addition, algae blooms (chlorophyll a > 8 ug/l) are projected for 27 miles of the river from Maysville to the international border with chlorophyll a levels as high as 20 ug/l predicted (Figure 14).  High levels of periphyton are also predicted by the model in free-flowing river sections below point source discharges which is consistent which what has been visually observed in the field.  The model predictions, laboratory data, and observations in the field all indicate that there is an  eutrophication issue on the Aroostook River from Presque Isle to the international border.

For the monthly average model run, river flows are input at the 30-day 10-year low flow (30Q10); point sources at the monthly average licensed limit, and river temperatures may be decreased from the levels assigned at 7Q10 flow.  The 30Q10 flow on the Aroostook is higher than the 7Q10 flow at the Washburn USGS gage by about 35%.  The flows on the Aroostook River 7Q10 input were increased by 35% for the monthly average run. There is no information available to determine how to assign monthly average temperatures.  The same temperature was used in the 30Q10 run as the 7Q10 run.  This should give slightly conservative results.

The monthly average model predictions are run in the steady state mode.  The model prediction run at 30 Q10 flow to check compliance with monthly average dissolved oxygen criteria of 6.5 ppm indicates that criteria will be met everywhere (figure 15).  In rivers with large amount of algae such as the Aroostook, monthly and daily average dissolved oxygen are not a compliance issue, since the amount of oxygen produced by the algae greatly exceeds the amount of oxygen consumed in the time period  considered.

Currently QUAL2MDEP does not have the capability to model pH.  The river pH issue is discussed in a later section of the report.

## Component Analysis

A component analysis is ordinarily undertaken for a water quality model to help determine which factors are the major contributors to the dissolved oxygen deficit. Various inputs or factors may be subtracted from the model and the difference in dissolved oxygen predicted by the model from a base case is observed.  It can then be

determined which inputs are significant and worth following up with remedial efforts in river cleanup situations.  In the case of the Aroostook River, there does not appear to be an issue with compliance of dissolved oxygen criteria.  However there is an issue with high algae levels in the river.  Phosphorus is ordinarily the limiting nutrient in fresh water systems, which must be reduced in order to alleviate eutrophication.

A component analysis  in the Aroostook is further complicated by the high amount of dissolved oxygen supersaturation that is predicted by the model.  Some of the parameter rates assigned to the model for the algae and periphyton systems are quite variable, and cannot be expected to remain constant for significant load reductions.  Which rates to use for significantly reduced point source inputs, for example, becomes problematic, since the model was not calibrated under these conditions.

For the cited reasons, the component analysis was undertaken by comparing input loads of point and non-point sources of ultimate BOD and total phosphorus.  It can be observed (Figure 16) in this analysis that at 7Q10 river conditions, McCain Foods and Presque Isle are the major source of phosphorus in the river, assuming that both are discharging at licensed flows with contributions of 43% and 17% of the total river phosphorus load, respectively.  Assuming that all discharges are discharging their licensed BOD5 loads at 7Q10 flow, McCain Foods, Loring, Caribou, and Presque Isle are all significant inputs with contributions of 29%, 15%, 15%, and 14%, respectively of the total ultimate BOD load (Figure 17).  For both phosphorus and BOD, base flow non-point and background sources are not significant, accounting collectively for 4% and 13% of the total river load for phosphorus and BOD, respectively.

## Model Predictions with Reduced Point Source Phosphorus

Different levels of point source reductions were investigated to determine the amount needed to alleviate eutrophication on the Aroostook River.  There are currently no direct numerical criteria in Maine's water quality standards that define an acceptable trophic state for rivers.  There are narrative criteria that allow for the regulation of nutrients.

The General Provision section of Maine's water quality classification standards 464(4A(4)) specifies that" the Department may not issue a waste discharge license for discharges to waters of the State that impart color, taste, turbidity, toxicity, and radioactivity or other properties that cause those waters to be unsuitable for the designated uses and characteristics ascribed to their class.  The Aroostoook River is classified as class C and B in the area of eutrophication.   Class C and B standards specify that the waters shall be suitable for the designated use of 'drinking water supply after treatment; fishing; recreation in and on the water (swimming) ; industrial process and cooling water supply; hydroelectric power generation, except as prohibited under Title 12, section 403; and navigation; and as a habitat for fish and other aquatic life'.

High concentrations of total phosphorus lead to excessive concentrations of phytoplankton or floating algae in low velocity areas commonly referred to as 'blooms' of algae.  The floating algae are transported with river flow.  Algae blooms impart color,

cause high turbidity, and result in overall conditions that cause waters to be unsuitable for swimming.  In flowing river sections, the conditions are more favorable for stationary algae that are attached to the river bottom rather than floating algae.  Bottom attached algae similarly result in designated uses of water contact recreation not being met.

Each state is being required by USEPA to derive numeric nutrient criteria by 2005.  In the interim, Maine has been using a chlorophyll-a level of 8 ppb to define the threshold level for algae blooms. A chlorophyll-a level of 8 ppb has been used in the lakes program as a threshold level for an algae bloom for more than two decades.  In addition, the 8 ppb chlorophyll a level is listed in the available literature as a threshold to prevent nuisance algae blooms in EPA's Nutrient Criteria Technical Guidance Manual for Rivers and Streams.  Recently DEP has applied a range of 8 to 12 ppb to describe blooms in a river impoundment.  It is uncertain at this time what chlorophyll a value should be used to describe eutrophic blooms in flowing waters.

Model prediction runs were undertaken with reduced phosphorus inputs from McCain Foods and  Presque Isle, who collectively in the component analysis section of the report have been identified as the two largest sources of phosphorus to the river.  These runs can provide some guidance as to the necessary reductions at the two major sources of phosphorus.  The results of the model prediction runs are summarized below (Table 10).

| Table 10   Summary of Model Runs with Reduced Point Source Phosphorus | | | |
|---|---|---|---|
| Model Run | Description | Maximum Chl.-a (ppb) | Maximum PO4-P (ppb) |
| ARO7qt | Point Sources at License | 20 | 169 |
| ARO7qtL | 50% Reduction TP for PISD, McCains | 20 | 89 |
| ARO7qtL1 | TP = 1 ppm PISD, McCains | 11 | 56 |
| ARO7qtL2 | TP = 0.5 ppm PISD, McCains | 9 | 33 |
| ARO7qtL3 | Non-point source & natural TP = 0 | 19 | 168 |
| ARO7qtL4 | TP Point Sources = 0 | 1 | 5 |

It can be observed up to a 80% reduction in river orthophosphorus levels may be necessary to approach levels of algae at the threshold bloom levels of 8 ppb chlorophyll-a.  In this case, Presque Isle and McCain Foods are inputted at a 0.5 ppm total phosphorus (TP) concentration and licensed flow.  Presque Isle is current meeting a 0.2 ppm requirement on Presque Isle Stream for PO4-P or a mass limit of 3.8 ppd.  Based upon a TP concentration of 0.5 ppm, the mass model input for Presque Isle is 9.6 ppd.  McCain Foods is current licensed for a summer monthly average TP limit of 91 ppd. Based upon a TP concentration of 0.5 ppm, the mass model input for McCains is 10.4 ppd. This collectively represents about a 84% reduction in point source phosphorus from baseline values for McCain Foods and Presque Isle.

The model runs show that with a 50% reduction of TP from McCain Foods and Presque Isle, virtually no reduction of algae will result, due to the large excess of phosphorus within the system. The river is no longer phosphorus limited at the high phosphorus input conditions and large reductions are needed before phosphorus limitation is reached. Also, with natural and non-point TP reduced to zero, there is also virtually no reduction in algae levels due to the large source of TP from point sources. With point sources reduced to zero, algae levels measured as chlorophyll-a are reduced to background concentrations of 1 ppb.

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## Summary of Results and Recommendations

Low early morning dissolved oxygen levels, that are under statutory criteria, does not appear to currently be an issue on the Aroostook, despite the high levels of floating and bottom attached algae observed and measured in impoundments and flowing river sections. Both the data collected and model predictions support this statement. Large reductions of point source phosphorus are needed to reduce algae to a non-eutrophic state. Non-point (runoff induced) phosphorus pollution, although not significant at base flow conditions, shouldn't be totally ignored.

The Aroostook River watershed is unique from most other modeling studies undertaken by MDEP on other rivers statewide. A large portion of the watershed in the Aroostook River is composed of agricultural and cleared land when compared to other watersheds. This results in a large potential for non-point source pollution.

As stated in the preceding sections, non-point pollution is currently not expected to be a significant contributor of water quality degradation during base flow conditions. During runoff events, the proportion of non-point source phosphorus and BOD loading to the river increases as compared to base flow conditions. However the river travel times are also decreased as river flow increases. As a result, a large portion of runoff loads during storm events may pass through without having a large impact on water quality.

It is presumed some proportion of the runoff loads will impact the river during base flow conditions. For example, particulate BOD and phosphorus could settle to the river bottom in impoundments or other areas with slow river velocities. Dissolved phosphorus may also be uptaken and stored in plant cells of bottom attached algae. The exact proportions are difficult to predict and is beyond the capability of the water quality model.

A plot in the data report comparing tributary wet weather and dry weather total phosphorus (Figure 18, Data Report) is repeated here for convenience (Figure 18, Modeling Report). By observing the difference in dry weather and wet weather total phosphorus concentrations, a ranking system was developed (high medium, low) for each tributary. The prior section indicated that non-point source reductions are not effective in reducing eutrophication, due to the large phosphorus loads from point sources that are

enough to generate large growths of phytoplankton and bottom attached algae even if non-point source loads could be entirely eliminated. It can be presumed as point source phosphorus is reduced, the non-point source runoff loads will become more important as pollution sources. Best management practices should be implemented first on tributary watersheds that are ranked as a high potential for pollution (Table 10).

The issue of high periphyton and bottom attached algae is more difficult to address without the criteria (to be developed in 2005) in place. As stated earlier in the report, high pH is often an issue in very productive river systems in the afternoon hours. The current modeling software of Qual2MDEP does not have the capability to model pH During the collection of stream transect data in 2002, one-half of the afternoon pH measurements from Presque Isle to Fort Fairfield exceeded the maximum allowable pH of 8.5 (Table 12). The range of pH in these exceedances was 8.5 to 9.

**Table 12 – Summary of pH Readings 2002**

| Location | Date | Time | Temp. ($^o$C) | pH |
|---|---|---|---|---|
| Presque Isle Str. confluence | | 9:45 | 19.8 | 7.8 |
| McCain Outfall | | 10:21 | 20 | 8.17 |
| Maysville | 8/30/02 | 11:40 | 20.3 | **9.0** |
| Below Caribou Dam | | 13:10 | 20.8 | 8.16 |
| Caribou Utilities | | 13:30 | 20.7 | **8.65** |
| L. Madawaska R. confluence | | 14:33 | 19.8 | 8.38 |
| Adjacent Parkhurst Rd, P. I. | 9/3/02 | 14:20 | 21.6 | **8.96** |
| Gray Brook confluence, Fort F | | 16:00 | 21.1 | **8.98** |

The best way of assuring that pH criteria are met and algae levels are not excessive in the Aroostook River is the collection of an additional data set at reduced point source inputs of TP. If possible, a data set should be collected with both McCain Foods and Presque Isle targeting a TP level of 1 ppm. Fort Fairfield has food processing manufacturing inputs to their treatment plant, which have the potential for high variability of TP as an uncontrolled source. If possible, Fort Fairfield should be practicing pollution prevention technologies to minimize phosphorus inputs during the collection of additional data

# Responses to Comments